PRECISION MEASUREMENT OF LUNAR AND SOLAR RADIO EMISSION IN THE 4-MILLIMETER BAND*

A. G. Kislyakov and V. M. Plechkov

ABSTRACT

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The measurements were made in August-September 1962 in the mountain region of Pamir (3860 meters above sea level). The emission of the sun and the moon was compared with that of a black disc of known angular dimensions. It was found that at a wavelength of 4 millimeters the brightness temperature of the sun is equal to 7300°K ± 200°K, while at the same wavelength the phase dependence of the radio emission of the moon is well described by the law $\bar{T}_e = [204 + 56 \cos (\Phi - 23^\circ)]^\circ K$, where $\bar{T}_e$ is the mean brightness temperature of the lunar disc and Φ is the lunar phase reckoned from full moon. The accuracy of the measurements of the absolute value of $\bar{T}_e$ was not less than 4 %. The results of the measurements were used to estimate the radio emissivity of the lunar soil and to calculate the phase dependence of the radio emission of the center of the lunar disc.

author

The need for precision measurements (correct to 2 or 3 %) of the radio emission of the moon over the widest possible range of wavelengths /46

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[redacted]

was established in [1, 2]. Observations of the lunar radio emission at a wavelength of 4 mm conducted in 1960-61 [3, 4] were insufficiently accurate (about 10 to 15 %) owing to defects in the method of calibrating the radiotelescope employed at that time. In August-September 1962 we made observations of the radio emission of the sun and the moon in the 4-mm band, using a method of precision measurement of the intensity of the radio emission developed in the Scientific Research Radiophysical Institute of N. I. Lobachevskiy Gor'kiy State University [5]. In order to realize the full potential of this method of observation, we selected a site in the mountains of Pamir (3860 meters above sea level).

The procedure adopted in measuring the lunar (and solar) radio emission was as follows. The antenna of the radiotelescope was aimed alternately at the moon and at a region of the sky in the vicinity of the moon. In this way we measured the difference in the output signals of a radiometer n_M for two positions of the moon: in and outside the antenna beam. The quantity n_M is proportional to the radio emission of the moon attenuated by absorption in the atmosphere. After this, the antenna was aimed at an "absolutely" black disc with angular dimensions of 50', located in the Fraunhofer region of the antenna (the distance of the disc was about 100 meters, the diameter of the antenna 0.5 meter). Then the disc was lowered behind a screen (see Fig. 1). In this case, the difference in the output signals of the radiometer n_D is proportional to the difference between the brightness temperatures of the disc and the sky at the level of the disc. On the basis of the results of [3, 5], it is possible to show that the brightness temperature of the moon averaged over the lunar disc

$$\bar{T}_e = \alpha \frac{n_M}{n_D} T_0 e^{-\Delta\gamma} \left[1 + \frac{bH}{T_0} s\,(\gamma_D) + \frac{\Delta t}{T_0} e^{\gamma_D} \right]. \qquad (1)$$

In this equation α is a coefficient which for a given antenna radiation pattern depends on the ratio of the solid angles of the standard disc of the moon, T_0 is the temperature in the layer of the atmosphere adjacent to the ground, $\Delta\gamma = \Gamma_0$ (sec ϑ_D - sec ϑ_M), where Γ_0 is the total vertical absorption in the atmosphere, and ϑ_D and ϑ_M are the /47 zenith distances to the centers of the disc and the moon, respectively, b is the gradient of the temperature drop in the atmosphere with increase in altitude, H is the effective height of the atmosphere, $\Delta t = T_D - T_0$, where T_D is the temperature of the material of the standard disc, and the function $s(\gamma_D) = \sum_{k=1}^{\infty} \frac{\gamma_D^k}{kk!}$.

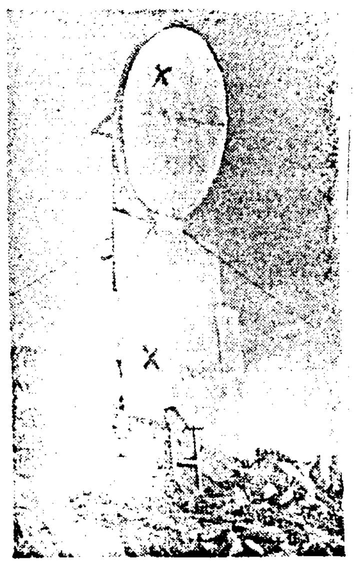

Fig. 1. General view of standard disc used to calibrate the radiotelescope.

In analyzing the experimental data the value of α was computed from the radiation patterns of the antenna found from records of the transit of the sun. The computations made allowance for the broadening of the patterns due to the fact that the angular dimensions of the solar disc are comparable with the width of the radiation pattern at the 3-decibel level. The quantities ϑ_M, T_0 and Δt were measured almost continuously during the course of the observations, and Γ_0

once or twice (usually at the beginning and end of the observations). The zenith distance of the disc was constant $\vartheta_D = 75^{\circ}$. We also assumed that b = 6.5 degrees/km, and that the effective heights of oxygen and water vapor in the atmosphere were 5 km and 2.2 km, respectively.

Observations of the moon were made once or twice a day; during each observation the lunar radio emission was fixed about 10 to 15 times. During August and September more than 50 such observations were made.

The results of the measurements of the lunar radio emission are summarized in Fig. 2, in which we have also plotted the curve

$$\bar{T}_e(\Phi) = [204 + 56 \cos(\Phi - 23^{\circ})]^{\circ}K, \qquad (2)$$

approximating the empirical dependence $\bar{T}_e(\Phi)$, where Φ is the lunar phase reckoned from full moon. As the graph shows, curve (2) deviates appreciably from the experimental points in the region of maximum radio emission. This may be due to the effect of the higher harmonics of the phase dependence, which are quite important in the 4-mm band [6]. At the same time, the considerable scatter makes it impossible to determine with sufficient reliability the amplitude of even the second harmonic.

The accuracy of the determination of the constant component of the brightness temperature of the moon is not less than ± 4 %. The principal -- fluctuational -- measuring error is ± 2.5 %. Moreover, we took into account possible inaccuracies in the determination of the distance to the disc (and hence in its angular dimensions), and in the value of ϑ_D, the width of the antenna radiation pattern, the atmospheric absorption, the parameters b and H, and the temperatures T_0 and T_D.

We shall now consider the results of measurements of the lunar radio emission in the 4-mm band from the point of view of the theory of the radio emission of the moon developed in [6, 7]. As is known [6], the mean brightness temperature of the lunar disc depends (correct to higher harmonics) on the phase in the following manner: /48

$$\bar{T}_e = (1 - R_\perp)\beta_0 T_= + (1 - R_\perp) \frac{T_1\beta_1}{\sqrt{1 + 2\delta + 2\delta^2}} \cos (\Phi-\varphi_1-\xi_1-\Delta\xi_1). \tag{3}$$

Here $(1 - R_\perp)$ is the emitting capacity of the center of the lunar disc, $(1 - R_\perp)T_=$ is the constant component of the brightness temperature of the central element of the surface of the moon, $(1 - R_\perp)T_1(1 + 2\delta + 2\delta^2)^{-1/2}$ is the amplitude of the first harmonic of the fluctuation of the radio temperature of the center of the lunar disc, β_0 and β_1 are certain coefficients depending on ϵ (the dielectric constant of the lunar soil), and δ (the ratio of the depths of penetration of the electric and thermal waves into the lunar soil). The angle φ_1 represents the shift between the phase of the illumination and the phase of the first harmonic of the surface temperature of the moon, $\xi_1 = \arctan [\delta/(1 + \delta)]$, and $\Delta\xi_1$ is the additional phase shift due to averaging the brightness temperature over the lunar disc. The quantity $\Delta\xi_1$ also depends essentially on ϵ and δ [6].

From relation (3) we can obtain:

$$\frac{\beta_0}{\beta_1} = \frac{M_{exp}T_1}{T_= \sqrt{1 + 2\delta + 2\delta^2}}, \tag{4}$$

where M_{exp} is the ratio of the constant component of the brightness temperature of the moon to the amplitude of the first harmonic found experimentally (i.e., from (2)). The quantities β_0 and β_1 were computed theoretically in [6], and the ratio $T_1/T_= \sqrt{1 + 2\delta + 2\delta^2}$ can be found, in accordance with [7], from the results of observations of the phase dependence of the radio emission of the central part of the moon [4]. Putting $\delta = 0.7$ [4] and using the ratio β_0/β_1 computed from equation (4), it is possible to find the corresponding ϵ_{eff}. The value of ϵ_{eff} determined in this way can then be used to estimate the emitting capacity of the lunar soil in the 4-mm band. /49

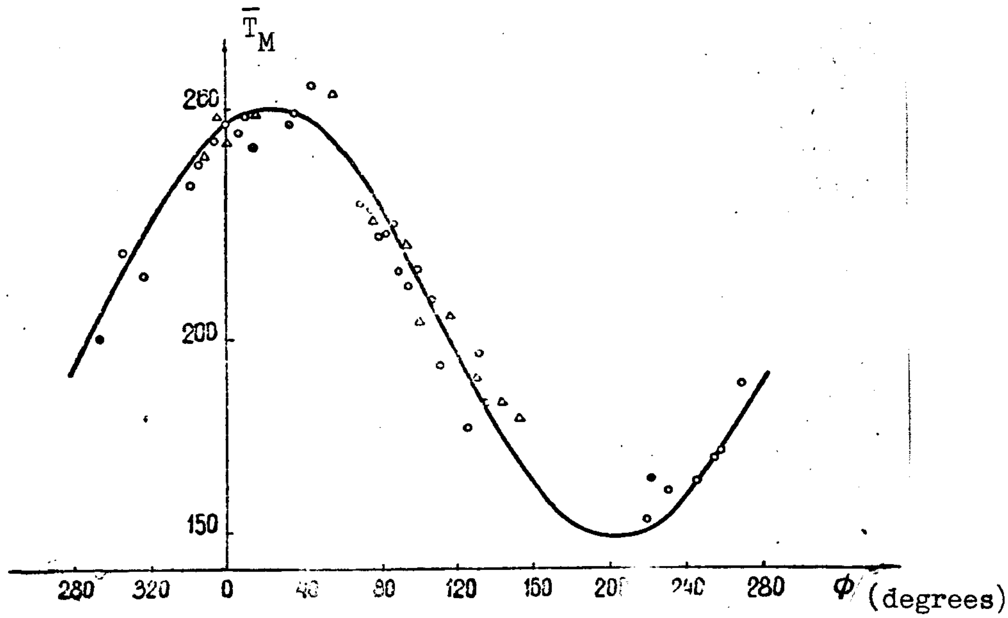

Fig. 2. Phase dependence of integral radio emission of moon at a wavelength of 4 mm: Δ experimental values obtained in August, o - obtained in September.

Thus, making use of (2), (4) and the results of the computations in [6], we find that $\epsilon_{eff} \simeq 6$. However, the accuracy of the measurement of M_{exp} and $T_1/T_= \sqrt{1 + 2\delta + 2\delta^2}$ is such that the value of the effective dielectric constant may lie within the limits $1 \leq \epsilon_{eff} \leq 20$.

If, however, we assume that $T_{=}/T_1 = 1.5$ [1, 2] and base ourselves only on measurements of M_{exp}, putting $\delta = 0.8$ [3, 4], then we find that $1.4 \leq \epsilon_{eff} \leq 12$, the most probable value being $\epsilon_{eff} \approx 3.5$.

Finally, there is another method of estimating ϵ_{eff} from the results obtained -- from the absolute value of the constant component of the brightness temperature $\overline{T}_e(\Phi)$, equal to $204^{o}K \pm 8^{o}K$. Assuming, in accordance with [8], that the nocturnal temperature of the moon $T_n = 125^{o}K$, while the temperature of a subsolar point $T_s = 391^{o}K$, and that the latitudinal distribution of the surface temperature of the moon is described by the law $\sqrt{\cos \psi}$, where ψ is the selenographic latitude, we find from Table 1 in [8] that $1.2 \leq \epsilon_{eff} \leq 2.5$, the most probable value being $\epsilon_{eff} = 1.8$. Hence we find that at a wavelength of 4 mm the mean reflection coefficient over the disc lies within the limits of $0.024 \leq \overline{R} \leq 0.103$, and the emitting capacity within the limits $0.897 \leq 1 - \overline{R} \leq 0.976$. In [8] the value of ϵ_{eff} for a wavelength of 3.2 cm was obtained in the same way. The most probable value is $\epsilon_{eff} = 1.4$, the full range being $1.1 \leq \epsilon_{eff} \leq 1.7$.

A comparison of the values of $(1 - \overline{R})$ determined from the results of precision measurements of the phase dependence of the radio emission of the moon at wavelengths of 3.2 and 0.4 cm apparently points to a certain decrease in the emitting capacity of the lunar surface with decrease in the wavelength of the observed emission. More definite conclusions can only be drawn on the basis of accurate measurements of the integral radio emission of the moon at wavelengths shorter than 0.4 cm, where the anticipated effect should be manifested more distinctly.

Following the example of [8], it is possible to use the values of ϵ_{eff} thus obtained to estimate the density of the material forming the surface of the moon. The Odelevskiy-Levin equation may be rewritten thus:

$$\frac{\rho}{\rho_0} = \frac{3\epsilon_0}{2\epsilon_0 + \epsilon_{eff}} \frac{\epsilon_{eff} - 1}{\epsilon_0 - 1}, \tag{5}$$

where $\epsilon_0 = 4.5$ and $\rho_0 = 2.5$ g·cm^{-3} are the dielectric constant and density of the lunar material in the dense state and ρ the true density. According to equation (5), for $1.2 \leq \epsilon \leq 2.5$ the density of the lunar material lies within the range $0.2 \leq \rho \leq 1.2$ g·cm^{-3}, the the most probable value being $\rho = 0.7$ g·cm^{-3}.

Now, let us use our estimate of ϵ_{eff} to compute the value of ξ_1 and the phase dependence of the radio emission of the center of the lunar disc. From [9] we know that $\varphi_1 = 3^o$, and $\Delta\xi_1 \simeq - 2^o$ (for $\epsilon_{eff} = 1.8$ and $\delta = 0.8$) [6]. Therefore, $\xi_1 = 23^o + 3^o - 2^o = 24^o$. Obviously, the phase shift for the radio emission at the center of the disc $\xi = 24^o + 3^o = 27^o$, which agrees with the value obtained in [4].

On the basis of our estimate of ϵ_{eff} we shall now recalculate (2) and obtain an expression for the phase dependence at the center of the lunar disc:

$$\overline{T}_e(\Phi) = 221^o + 74^o \cos (\Phi - 27^o), \tag{6}$$

which, within the limits of error, coincides with the result obtained in [4]. Note that (6) is a more reliable expression for the phase dependence of the radio emission of the center of the moon than that presented in [4]. /50

To conclude, a few words concerning the measurements of the radio emission of the sun in the 4-mm band. These measurements were not systematic and were made only over a period of several days at the end of September 1962. As a result of the measurements we found that at a wavelength of 4 mm the brightness temperature of the sun has a value of 7300°K ± 200°K. Since this is the first precision measurement of the brightness temperature of the sun to be made in the 4-mm band, it is still difficult to draw any conclusions concerning the slow variations of the integral solar radio emission in this band.

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Scientific Research Radiophysical Institute of
Gor'kiy University
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<u>Note added to proofs:</u> Since expression (6) for the phase dependence of the radio emission of the center of the lunar disc is more reliable than that presented in [1], it is possible to refine the value of the brightness temperature of Venus obtained in [2] by comparing

the antenna temperatures recorded upon aiming the antenna at the center of the lunar disc and at Venus. The improved value of the brightness temperature of Venus is $370^{\circ}K \pm 90^{\circ}K$.

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